

**CORRELATION BETWEEN
CONCRETE DURABILITY AND
AIR-VOID CHARACTERISTICS
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by

F. K. Fears

**Joint
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Project**

PURDUE UNIVERSITY
LAFAYETTE INDIANA



TECHNICAL PAPER

CORRELATION BETWEEN CONCRETE DURABILITY AND
AIR-VOID CHARACTERISTICS

TO: K. B. Woods, Director
Joint Highway Research Project

FROM: H. L. Michael, Assistant Director

December 18, 1957

File: 5-6-17
Project C-36-374

The attached technical paper entitled, "Correlation Between Concrete Durability and Air-Void Characteristics," has been prepared by Mr. Fulton K. Fears, a former graduate assistant on our staff. The paper is a summary of Mr. Fears' thesis that was previously submitted and will be presented at the Highway Research Board Annual Meeting in January, 1958.

The paper is submitted for the record.

Respectfully submitted,

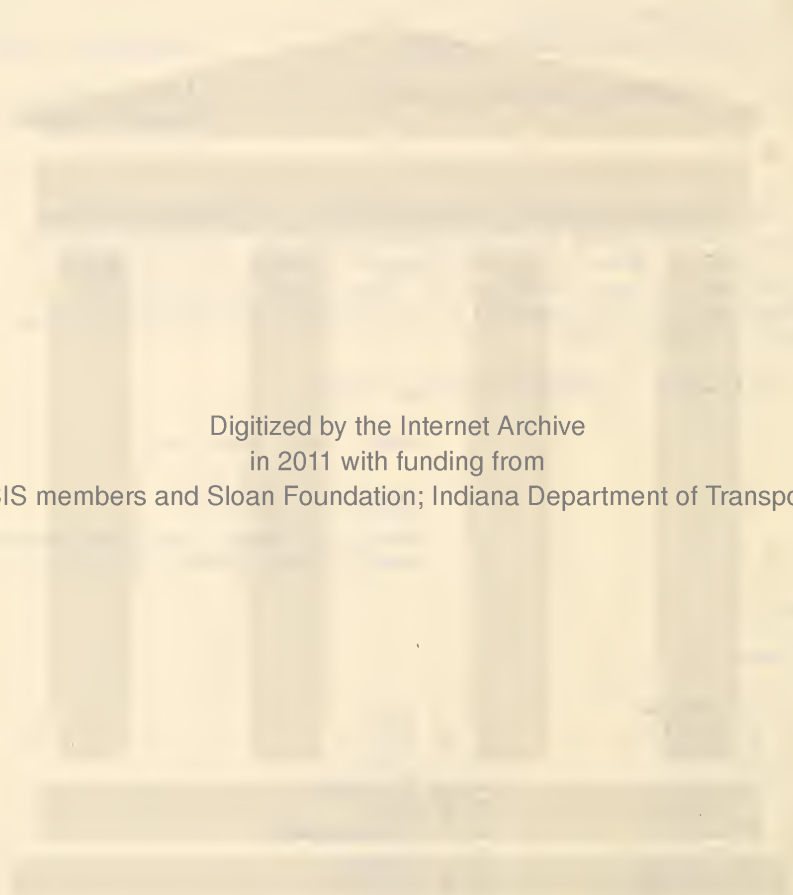
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Attachment

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TECHNICAL PAPER

CORRELATION BETWEEN CONCRETE DURABILITY AND
AIR-VOID CHARACTERISTICS

by

Fulton K. Fears
Former Graduate Assistant

Joint Highway Research Project
File: 5-8-17
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Purdue University
Lafayette, Indiana

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CORRELATION BETWEEN CONCRETE DURABILITY AND AIR-VOID CHARACTERISTICS

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INTRODUCTION

Numerous investigators have reported (4,5, 7, 9, 10, 11, 25)* laboratory studies showing increases in durability and resistance to scaling which result from entraining air in concrete mixes. Several of these studies (4, 5, 7) show that resistance to deterioration under repeated cycles of freezing and thawing of concrete made with poor aggregates is sometimes greatly increased by air entrainment. Andrews' report (3) of the performance of concrete test roads in the northeastern states built with a wide range of variables shows a comparison of the field performance of air-entrained concrete with adjacent sections of the same construction but without air entrainment. The report shows that high resistance to the severe exposure of repeated cycles of freezing and thawing and salt action in ice removal has been given to these concrete pavements over a period of ten to fourteen years by air entrainment. Jackson (10) and Gonnerman (9) report that the performance under service conditions of experimental paving projects constructed with air-entrained portland cement parallels the results of the laboratory studies. Thus the superior performance in general of air-entrained concrete has been demonstrated in both the field and the laboratory.

Reports of research on air entrainment deal principally with factors which control the amount of air or with changes in properties of

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*Numbers in parentheses refer to the list of references at the
end of the paper.

the concrete related to changes in the gross amount of air. However, theoretical and practical considerations suggest that the properties of the air voids themselves are important factors influencing the ability of concrete to withstand freezing and thawing conditions (11, 13, 14, 15, 16).

Considerable research on the effect of air entrainment on the durability of concrete beams as measured by resistance to deterioration under repeated cycles of freezing and thawing has been performed in the laboratories of the Joint Highway Research Project at Purdue University. The studies reported by Blackburn (5) and Bugg (7) show increases in the laboratory durability of air-entrained concrete made with limestone aggregates which have poor to fair field service records over concrete made with the same materials but without the inclusion of air.

Subsequent studies of the effect of air entrainment on the durability of concrete made with aggregates with poor to fair field performance records have shown at times considerable differences in durability between beams from the same mix and between mixes containing the same materials and which have the same total air content as determined by measurements on the fresh concrete. Hence, this study was initiated to determine which property of the entrained air is most significant in producing durable concrete and to what extent differences in durability can be explained by differences in the air-void characteristics of the beams. The air-void characteristics either measured or calculated were: (a) total air content, (b) number of voids intersected per inch, (c) specific surface, (d) hypothetical number of voids per cubic inch, and (e) void spacing factor.

Theory

Entrained air appears to exist in the form of small, disconnected air bubbles distributed throughout the concrete paste (20). The natural voids found in concrete made without an air-entraining agent vary considerably among different mixes but are generally larger than the bubbles produced by air entrainment (16). These natural voids result from the entrapping of air in the concrete mix. In the air-entrained concrete the composite system of voids is a combination of the natural voids and entrained air bubbles. Warren (22) found that the average diameter of the voids for a series of air-entrained mixes varied from 0.04 millimeters to 0.10 millimeters.

Powers and Helmuth (13, 15) explain the freezing of water in hardened portland-cement paste in terms of two mechanisms: (a) the generation of hydraulic pressure as water freezes in capillary cavities, and (b) the growth of bodies of ice in the capillary cavities or air voids by diffusion of water from the gel pores. A brief review of these two mechanisms follows.

Hardened portland-cement paste is made up of extremely tiny spheres linked together to form the cohesive mass called cement gel. When the cement gel completely fills the space available to it the porosity of the paste is about 25 percent. In most pastes the volume of the gel does not equal the apparent volume. The unfilled space in the paste occurs as cavities which are called capillary pores. The gel pores are the interstitial spaces among the massed spheres which surround the cavities.

The gel pores are so small that water cannot freeze in them at ordinary temperatures. Thus, at these temperatures, the capillary

pores or cavities are the only places where ice can exist within the boundaries of the paste. However, the capillary pores are also so small that the ice crystals which they contain can exist only when the temperature is below the normal freezing point. Air voids such as those in air-entrained concrete are extremely large compared with the capillary pores and gel pores in the paste.

In a water-soaked paste the capillary pores and the gel pores are full, or nearly full, of water. When the water in a saturated capillary pore begins to change to ice the volume of the water plus ice will exceed the original capacity of the cavity. This comes about because one cubic centimeter of water occupies about 1.09 cubic centimeters of space after freezing. Therefore, during the time the water is changing to ice, the cavity must dilate or the excess water must be expelled from it. Although the coefficient of permeability of the cement gel is extremely low there is the possibility that the excess water can escape from the capillary cavity during freezing. The growing ice body in the capillary cavity may be considered as a sort of pump forcing water through the cement gel toward an air-void boundary. Such a pumping action involves the generation of pressure. In general, during the process of freezing, hydraulic pressure will exist throughout the paste, and this pressure will be higher the farther the point in question is from the nearest air-void boundary where the pressure is relieved. By reducing the distance between air voids to the point where the protected shells surrounding air voids overlap, the generation of disruptive hydraulic pressure during the freezing of water in the capillaries can be prevented.

The generation of hydraulic pressure through the previously described mechanism does not account for all the phenomena that accompany freezing.

Powers and Helmuth (15) suggest that part of the disruptive effect of freezing is caused by the tendency of microscopic bodies of ice to grow by diffusion of water from the gel pores to the capillary cavities, producing expansion. This may occur at any temperature below the temperature at which the ice in a cavity was formed.

The functions of the entrained-air voids are (a) to limit the hydraulic pressure in the paste during the initial stages of freezing; and (b) to limit or prevent the growth of microscopic bodies of ice in the paste while the temperature is below the normal freezing point. Powers (14) has derived a formula from which can be calculated the theoretical maximum distance from any point in the paste to an air-paste interface which can occur without disruptive hydraulic pressure being generated. For this void spacing factor he has suggested an upper limit of 0.01 inches. This value may also be considered satisfactory for the prevention of damage due to the growth of ice bodies.

Development of the Linear Traverse Technique

The methods which have been used for the measurement of air in hardened concrete have been based on the procedures followed by the geologists in the measurement of minerals in rocks. Lincoln and Rietz (12) reviewed the development of the mensuration methods used by the geologists in an article in Economic Geology in 1913. They reported that the first mensuration method to make use of physical measurements was the areal method of Delesse in 1848. Delesse applied a transparent sheet of paper of goldbeater's skin to the polished or nearly plane surface of a rock and traced upon it the outline of the various mineral grains. The sketch was then tinted so that the various minerals could be identified, and the

sheet pasted with soluble gum to a piece of tin foil. The variously tinted surfaces with their adhering tin foil were next cut apart and grouped according to their colors, the paper washed away, the tin foil particles in each group weighed, and the percentages of the various mineral compounds of the rock computed directly from these weights.

The linear mensuration method was devised by Rosiwal (18) in 1898 for the measurement of the minerals in a rock. It consisted of measuring the intercepted lengths of grains along a line or series of lines and calculating the percentage by volume by dividing the total distance into the sum of the intercepts for each component. Rosiwal presented a proof by calculus to show that intercepts on lines are proportional to volumes. Lincoln and Rietz (16) presented an alternate geometrical proof.

Shand (19) developed a recording micrometer which could be used to add the intercepts for a given mineral as well as to make the measurements. This instrument was used with a microscope in the examination of thin sections of rock. Wentworth (23) improved on the recording micrometer by developing an accessory stage whereby separate micrometers accumulated intercepts for assigned minerals.

There have been several methods applied to the determination of air voids in hardened concrete. Verbeck (20) reported a visual method for determining the amount of air by planimetering camera lucida tracings of polished sections of concrete. Warren (22) used a procedure whereby the air voids exposed by a polished surface were filled with a fluorescent material and photographed under ultra-violet light. Measurements were then made on the photographs to determine the air-void parameters.

Rexford (17) observed thin sections of the cement paste and made the measurements with the Wentworth recording micrometer.

Brown and Pierson (6) applied the principle of the Wentworth recording micrometer to the construction of a linear traverse integrator of special design with two recording motions, one for the air voids and one for the solids. This instrument is used in conjunction with a binocular microscope, generally working at a magnification of 30 to 40 diameters. The use of this apparatus permits the observation of surfaces large enough to afford true representation of aggregate and also of the occasional large air void that occurs in practically all concretes. The binocular microscope greatly facilitates the perception of air voids. The amount of work involved in the preparation of the surface of the specimen is less than that required by the other methods. Therefore, equipment and procedures similar to those recommended by Brown and Pierson were used in this study.

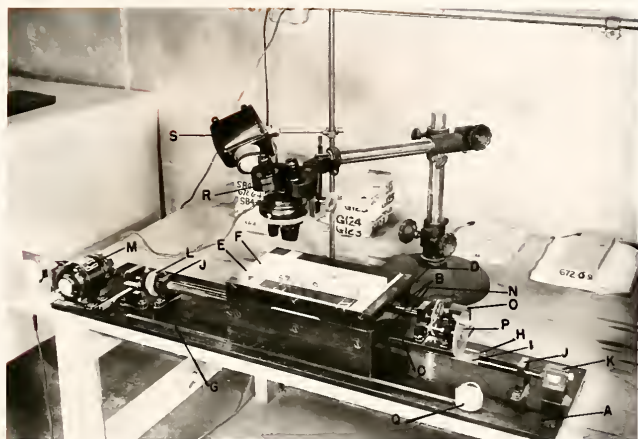
EQUIPMENT AND TECHNIQUES

The apparatus for the measurement of the air content and the number of voids per inch is shown in Figure 1. The three principal parts which make up the linear traverse integrator are the grooved base plate (A), the lower front and back rails (B) to which the middle plate (C) is attached, and the upper front and back rails (D) carry the top plate (E) on which the concrete specimen (F) is placed. The lower rails ride in two grooves in the base plate. The front groove (G) is rectangular in shape while the back groove (H) is V-shaped to aline and guide the rails.

The main lead screw (I) is attached to the base plate by two bearing blocks (J). At the right end is a revolution counter (K) which is used to record the distance traveled by the lower rails and middle plate which represents the distance across the solid constituents of the concrete. Power is supplied either manually by rotating a knurled wheel (L) or by an electric motor (M) at the left of the screw. One revolution of the main lead screw produces a tenth of an inch of translation.

The middle plate, to which the lower rails are attached, carries the top plate lead screw (N), a second revolution counter (O), and a hand wheel (P) for controlling the movement of the top plate relative to the middle plate. The second revolution counter is used to record the distance across the air voids in the concrete. One revolution of the top plate lead screw produces a hundredth of an inch movement of the top plate. A ratchet counter (Q) is used to tally the number of air voids encountered in a traverse.

A binocular microscope (R) is used with 3X objective lenses and 15X eyepieces to produce a magnification of 45 diameters. Crosshairs





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intersecting at 90 degrees are mounted in one eyepiece so that the crosshairs make an angle of 45 degrees with a line in the direction of movement of the intersection. A spotlight-type microscope lamp(S) is positioned to throw a beam of light on the specimen at a low angle so that the shadows facilitate the recognition of the air voids.

In using the linear traverse integrator the concrete specimen is moved to the right or left as desired by means of the main lead screw until, through the microscope, the observer sees an air void coming into the field of view. He stops the motion with the main lead screw when the intersection of the crosshairs is at the edge of the air void. He then uses the hand wheel on the middle plate to move the intersection of the crosshairs to the opposite edge of the air void, and one void is tallied on the ratchet counter. Motion is resumed with the main lead screw until the intersection reaches another air void and the process is repeated. A small scale is used to measure the distance from the edge of the top plate to the concrete specimen in order to obtain uniformly spaced traverses.

The distance in inches across the solid components is found by dividing by ten the number of revolutions recorded on the revolution counter at the right end of the main lead screw. The distance across the air voids in inches is obtained by dividing by one hundred the reading on the second revolution counter. The sum of the two distances gives the total length of the traverse. The distance across the air voids divided by the total length of the traverse is an estimate of the total air content of the concrete. The number of voids per inch is computed by dividing the total number of voids by the total length of the traverse.

In this study, slabs approximately one inch thick were cut from concrete beam specimens by means of a masonry saw. A wet-cutting steel bond diamond blade was used on the saw. The size of the beams from which the slabs were cut was 3 x 4 x 16 inches. First, approximately three inches were removed from each end of the beam. Then longitudinal cuts were made through the three-inch dimension to produce a one-inch slab from the center portion of the beam. The sawed surfaces, approximately 3 x 10 inches, on each side of the slab were used for determining the air-void characteristics of the beam. Modifications in sawing were necessary depending on the degree of deterioration of the individual beam.

The initial polishing of each surface was done on hard plate glass 24 inches square using Grade No. 180 aluminum oxide powder. Water was used as a lubricating and dispersing medium during grinding and for washing the polished surface. After twenty minutes of polishing, the surface was thoroughly washed using a nozzle to produce a pressure to aid in removing the grinding powders from the voids. The washing procedure was repeated after another twenty minutes of polishing. The above procedure was then repeated using Grade No. 240 aluminum oxide powder. Thus, a total of eighty minutes was spent in polishing on each surface with two grades of grinding powders.

The final polishing was done with a portable belt sander. A wooden jig was used for holding the slabs in place while the polishing was being done. Silicon carbide abrasive belts Grit No. 240 were used. One belt was used to polish two surfaces alternating between the two surfaces so that a total of ten minutes of polishing was done on each surface.

This procedure produced polished surfaces on which the voids were

sharply defined and measurements on a given traverse could be repeated with practically the same result for the air content and the number of voids per inch.

Studies of Position and Length of Traverse

The Rosiwal method of determining the percentage by volume of the constituents of a solid requires that a random line be passed through the solid. This principle is applied to a sample of concrete by first exposing a random section and then running a random traverse line in the plane of the section. In the actual application to a given beam the four surfaces of the beam are considered to have been randomly selected with respect to the concrete mix from which the beam was made.

In order to determine the effect, if any, of the position of the traverse within the beam an investigation of the variability of the air content and number of voids per inch within the beam was made. Also, the effect of the length of traverse on the reliability of the measurements was studied. For this investigation two beams from a concrete mix containing a durable coarse aggregate were selected for examination. Each of these beams had withstood 800 cycles of freezing and thawing without any loss in dynamic modulus of elasticity.

The original beam dimensions were 3 x 4 x 16 inches. Three inches were removed from each end of the beams by sawing. Then three cuts were made longitudinally through the three-inch dimension so that four slabs approximately $3/4$ -inch thick were produced from each beam. Three surfaces from each beam were polished for examination by the linear traverse integrator. The three surfaces selected for examination were those which could be considered to represent three vertical planes spaced through the beam at approximately one-inch intervals. These planes are

designated 1', 2', and 3' in Figure 2.

To study the effect of using traverses of different lengths, determinations of the air content were made using traverses of four different lengths. Four equally spaced traverses were measured on each polished surface. Thus the twelve traverses in each beam could be considered to fall within three vertical or four horizontal planes as shown in Figure 2.

An estimate of the air content of each beam was made using the first four inches of each traverse starting at the right edge and moving the beam to the right. Estimates were then made using the first six inches of each traverse. Then the first eight inches of each traverse were used. Finally all ten inches of each traverse were examined. The estimates for each traverse are given in Table 1.

Statistical Analysis

The statistical procedure known as the "analysis of variance" (8) for testing for significant differences among two or more means was followed to determine if the measured air content is influenced by the position of the traverses with respect to horizontal or vertical planes within the beam. The analysis is based on the fact that if means of subgroups are greatly different, the variance of the group means is much larger than the variances within separate groups. In this particular study the subgroups are horizontal or vertical planes.

The results of this type of analysis are usually presented in an analysis of variance table (see Tables 2 and 3). The values shown in the columns headed "Mean Square" are measures of the variability among the data which may be attributed to the factors listed in the column headed "Source of Variation." The number of degrees of freedom is one less

TABLE 1

AIR POLLUTION ESTIMATES (PERCENT) INDIVIDUAL TRAVELERS
OF DIFFERENT LENGTHS

Length of Travel (miles)	Hours of Travel	Base					Total
		1	2	3	4	5	
Four	1	3.85	4.52	7.25	4.70	2.85	13.17
	2	6.94	8.75	7.25	4.98	0.75	18.67
	3	0.75	2.99	3.46	1.75	1.27	10.22
	4	2.93	2.99	2.57	1.94	0.09	10.52
Six	1	3.17	2.32	6.25	5.47	4.13	3.65
	2	1.83	4.29	2.64	2.48	0.83	3.81
	3	1.17	3.17	3.82	3.50	2.15	2.32
	4	4.13	3.01	2.00	4.29	3.17	3.65
Eight	1	3.99	2.59	3.29	1.75	2.15	1.75
	2	2.25	3.25	3.25	1.75	2.00	5.75
	3	1.62	2.75	3.25	1.27	2.15	1.15
	4	1.31	2.50	2.50	1.81	2.00	1.75
Ten	1	3.00	2.50	3.00	1.75	1.75	1.75
	2	2.25	1.75	1.75	1.75	1.75	1.75
	3	3.00	1.75	1.75	1.75	1.75	1.75
	4	5.17	1.75	1.75	1.75	1.75	1.75



1871 1872 1873 1874 1875 1876
1877 1878 1879 1880 1881 1882
1883 1884 1885 1886 1887 1888
1889 1890 1891 1892 1893 1894

TABLE 2
ANALYSIS OF VARIANCE--AIR CONTENT (PERCENT)--
HORIZONTAL PLANES

Length of Traverses (Inches)	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Four	Beams	0.7597	1	0.7597	0.24
	Pl. in Bm.	18.8063	6	3.1344	1.14
	Tr. in Pl.	<u>44.1423</u>	<u>16</u>	2.7589	
	Total	63.7083	23		
Six	Beams	0.1135	1	0.1135	0.06
	Pl. in Bm.	10.5382	6	1.7564	1.09
	Tr. in Pl.	<u>25.7296</u>	<u>16</u>	1.6081	
	Total	36.3813	23		
Eight	Beams	0.8893	1	0.8893	0.53
	Pl. in Bm.	9.9966	6	1.6661	1.43
	Tr. in Pl.	18.6942	<u>16</u>	1.1684	
	Total	29.5801	23		
Ten	Beams	0.0084	1	0.0084	0.01
	Pl. in Bm.	6.5401	6	1.0900	0.83
	Tr. in Pl.	<u>21.0441</u>	<u>16</u>	1.3153	
	Total	27.5926	23		

$$F_{(4,18)} = 2.93$$

0.95

$$F_{(6,16)} = 2.74$$

0.95



TABLE 3
ANALYSIS OF VARIANCE--AIR CONTENT (PERCENT)
VERTICAL PLANES

Length of Traverses (Inches)	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Four	Beams	0.7597	1	0.7597	0.14
	Pl. in Bm.	21.9916	4	5.4979	2.42
	Tr. in Pl.	<u>40.9570</u>	<u>18</u>	2.2754	
	Total	63.7083	23		
Six	Beams	0.1135	1	0.1135	0.07
	Pl. in Bm.	6.2004	4	1.5501	0.93
	Tr. in Pl.	<u>30.0674</u>	<u>18</u>	1.6704	
	Total	36.3813	23		
Eight	Beams	0.8893	1	0.8893	0.73
	Pl. in Bm.	4.8686	4	1.2172	0.92
	Tr. in Pl.	<u>23.8222</u>	<u>18</u>	1.3235	
	Total	29.5801	23		
Ten	Beams	0.0084	1	0.0084	0.00
	Pl. in Bm.	7.4788	4	1.8697	1.67
	Tr. in Pl.	<u>20.1054</u>	<u>18</u>	1.1170	
	Total	27.5926	23		
$F_{0.95}(4,18) = 2.93$ $F_{0.95}(6,16) = 2.74$					

than the number of values involved in the computation of the sum of squares. The mean square is obtained by dividing the sum of squares by the corresponding degrees of freedom for the given factor. The F ratio is used to test for significance. It is formed in this case by taking the mean square found on the line whose effect is being tested and dividing by the mean square of the next lower subgroup in the sampling procedure. If this ratio is less than the F ratio at some chosen level of significance based on the Fisher variance ratio probability law, then it may be concluded that the particular factor being tested is not significant. In this case, for instance, reference to Table 2 shows that the measured air content is independent of the particular horizontal planes from which the traverses were selected.

The F ratios for a significance level of 5 percent are $F_{(4,18)} = 2.93$ for vertical planes and $F_{(6,16)} = 2.74$ for horizontal planes. Inspection of Tables 2 and 3 does not show any F ratio which is significant at the 5 percent significance level. Similar results were obtained in the study of the variability of the number of voids intersected per inch. Hence, it may be concluded that air content and number of voids per inch may be determined without regard to the horizontal or vertical planes within which the traverses may fall.

A 90 percent confidence level for determining the air content of an individual beam within ± 0.5 percent of the true air content was selected. Table 4 presents the results of the study of the effect of the length of the individual traverse on the confidence limits for the mean air content. The standard error of the mean is shown to decrease as the length of the traverse is increased with the total number of traverses remaining the same. When the standard error of the mean is computed on the basis of a total of 120 inches of traverses, it is approximately 0.3 for tra-

TABLE 4

CONFIDENCE LIMITS FOR AIR CONTENT (PERCENT)
— TRAVERSES OF DIFFERENT LENGTHS

Length of Traverses (Inches)	Error of Mean Square	Std. Error of Mean, $S_{\bar{x}}$	Confidence Limits for Beam (90% Confidence Level)	$S_{\bar{x}}$ for 120 Inches of Traverses	Total Length of Traverses Required for 90% Confidence Intervals to be 1% Long (Inches)
Four	2.861	0.483	3.18 ± 0.83	0.309	136
Six	1.649	0.371	3.22 ± 0.63	0.287	120
Eight	1.304	0.330	3.55 ± 0.56	0.295	124
Ten	1.254	0.323	3.60 ± 0.55	0.323	150
Average				0.303	133

verses of all lengths. Very similar results were obtained for the number of voids per inch. Therefore, the total length of the traverses determines the confidence limits for the air content and number of voids per inch rather than the length of an individual traverse.

The measurement of the air content and number of voids per inch of an individual beam may be considered as one long traverse. Table 4 shows that the total length of this traverse should be approximately 135 inches to give the air content of a beam of the type studied within ± 0.5 percent of the true air content. In order to allow for some increase in variability when examining concrete from other mixes, one hundred inches of traverses on each of two surfaces (200 inches total) were selected as standard procedure for the measurements.

To provide a check on the selection of 200 inches as the total length of the traverses to be measured for a given beam, three additional surfaces (Planes A, B, and C, Figure 2) from each beam were polished and ten traverses, each ten inches in length, were measured on each surface. The planes within each beam were combined in pairs and the confidence limits computed as given in Table 5. The air content and the number of voids per inch are shown to be within the limits of ± 0.5 percent and ± 0.5 void per inch, respectively. Also, it may be noted that when any two planes are combined the difference from any other combination for the given beam is small.

In order that some comparison might be made between the measurements reported in this study and those made in other laboratories, six concrete specimens were obtained from the Portland Cement Association Laboratory. The results of the measurements made on these specimens are reported in Table 6. One hundred inches of traverses were run on

TABLE 5

CONFIDENCE LIMITS FOR AIR CONTENT (PERCENT) AND NUMBER OF VOIDS
PER INCH--INDIVIDUAL BEAMS--TWO HUNDRED INCHES
OF TRAVERSES ON TWO PLANES

Beam	Two Planes Combined	Air content (Percent) (Confidence Limits for Beam-- 90% Confidence Level)	Number of Voids per Inch (Confidence Limits for Beam-- 90% Confidence Level)
I	A and B	3.41 ± 0.39	4.34 ± 0.35
	A and C	3.46 ± 0.42	4.46 ± 0.40
	B and C	3.65 ± 0.42	4.47 ± 0.38
II	A and B	4.11 ± 0.41	5.74 ± 0.25
	A and C	3.93 ± 0.36	5.58 ± 0.26
	B and C	3.92 ± 0.36	5.47 ± 0.30

TABLE 6

CONFIDENCE LIMITS FOR AIR CONTENT (PERCENT) AND NUMBER OF VOIDS
PER INCH--SPECIMENS FROM PCA LABORATORY--TWO
HUNDRED INCHES OF TRAVERSES ON TWO PLANES

Specimen	Air Content (Percent) (Confidence Limits for Specimen-- 90% Confidence Level)	PCA Values for Air Content (Percent)	Number of Voids per Inch (Confidence Limits for Specimen-- 90% Confidence Level)
8	3.53 $\pm$ 0.65	3.6	1.26 $\pm$ 0.11
2	1.52 $\pm$ 0.35	1.6	0.69 $\pm$ 0.12
S-8	1.09 $\pm$ 0.24	1.0	0.67 $\pm$ 0.09
U-15	4.48 $\pm$ 0.51	4.8	6.80 $\pm$ 0.51
83	2.14 $\pm$ 0.42	2.3	1.13 $\pm$ 0.13
30-A	8.43 $\pm$ 0.67	8.0	11.91 $\pm$ 1.04

each of two surfaces of each specimen. The results substantiate the procedure developed in this study. Also, the air content measurements check very closely with those obtained in the Portland Cement Association Laboratory.

MATERIALS

Concrete beams which were fabricated for use in another investigation conducted in the concrete laboratory of the Joint Highway Research Project were selected for examination in this study. These beams were chosen because of unexplained differences in durability between beams containing the same materials and the same total air content as determined by measurements on the fresh concrete. It appeared that examination of these beams would provide information of particular value regarding the previously stated objective of determining which property of the entrained air is most significant in producing durable concrete.

All beams used in this study were made with crushed stone coarse aggregates. Data on these aggregates are presented in Table 7. The six coarse aggregates from the sources in the Kokomo limestone formation have poor durability records. The source from the Liston Creek formation has a good field performance record.

The fine aggregate used in all mixes was obtained from a river terrace deposit of glacial origin. This fine aggregate has been used in the Joint Highway Research Project concrete laboratory for years as a standard material and is considered to be a durable material in laboratory freeze-thaw weathering. The bulk saturated surface dry specific gravity of the fine aggregate was 2.65 and the fineness modulus for the gradation was 3.10. The absorption was 1.65 percent by weight.

Type I portland cement from a single clinker batch was used in all mixes. Darex and neutralized vinsol resin solution were used as air-entraining agents.

COARSE AGGREGATES

Aggregate Designation	Aggregate Source Number	Laboratory Sample Number	Description	Geological Origin	Bulk Sp.Gr.	True Sp.Gr.	Absorption After Evacuation and Saturation (Percent by Wt.)	Degree of Saturation (Percent)
A ₁	9-2S	2033-A	Upper 25 feet-- Ledges 1, 2, 2, 4	Silurian (Kokomo Formation)	2.63	2.86	2.69	90
A ₂	9-2S	2033-B	Lower 21 feet-- Ledges 5, 6, 7	Silurian (Kokomo Formation)	2.53	2.86	4.66	98
A ₃	9-2S	2033-C	Stockpile Sample	Silurian (Kokomo Formation)	2.57		3.95	
A ₄	9-1S	2034	Ledge sample	Silurian (Kokomo Formation)	2.45	2.86	5.85	100
A ₅	9-5S	2032-A	Upper 24 feet--Silurian Ledges 1, 2, 3, 4	Silurian (Kokomo Formation)	2.59	2.85	3.19	88
A ₆	9-5S	2032-B	Lower 24 feet--Silurian Ledges 5, 6, 7	Silurian (Kokomo Formation)	2.46	2.85	5.65	100
A ₇	1-1S	2037	Stockpile Sample	Silurian (Linton Creek Formation)	2.68	2.85	1.98	90

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Concrete Mixes

All coarse aggregates were vacuum saturated before being incorporated in concrete mixes designed for a water-cement ratio of 0.46 by weight, a cement factor of six bags per cubic yard, and a slump of three to four inches. The maximum size of aggregate was one inch. The air content of the fresh concrete was measured gravimetrically according to A.S.T.M. Designation: C:138-44, (1) except that a 0.1 cubic foot measure was used because of the small size of the concrete mixes. The concrete used for making the air content determination was discarded. Three concrete beams, 3 x 4 x 16 inches, were made from each mix. Curing was by immersion in water for 13 days following removal of the specimens from molds one day after casting.

MEASUREMENT OF DURABILITY

The relative durability of the beams was determined from their resistance to deterioration when subjected to repeated cycles of freezing and thawing. Automatic equipment was used with the freezing and thawing cycles corresponding to A.S.T.M. designation C291-52T (1) rapid freezing in air and thawing in water. Approximately seven cycles per day were obtained.

Periodic determinations of the dynamic modulus of elasticity were made to measure the amount of deterioration. In most cases freezing and thawing was continued until a decrease in dynamic E to 50 percent of the original value occurred or until 800 cycles of freezing and thawing were completed.

The seven coarse aggregates described in Table 7 were represented by 19 mixes. The number of mixes using each coarse aggregate varied. Referring to the aggregate designations in Table 7, A_1 was used in two mixes, A_2 in three mixes, A_3 in two mixes, A_4 in three mixes, A_5 in three mixes, A_6 in five mixes, and A_7 in one mix. For use in studying the air-void characteristics two beams were selected from each mix--the most durable and the least durable. Thus, a total of 38 beams from the 19 mixes were studied.

A durability factor was used to express the durability of each beam selected for measurement of the air-void characteristics. This factor was computed following the procedure suggested by Stanton Walker (21). It may be defined as the area under the curve (dynamic E as a percent of the original E plotted against cycles of freezing and thawing) to the left of the 200th cycle and above the 50 percent dynamic E line expressed as a percentage of the total area to the left of the 200th

cycle and above the 50 percent dynamic E line. Table 8 gives the durability factors for the 38 beams which were selected for the measurement of the air-void characteristics.

AIR-VOID CHARACTERISTICS AND DURABILITY FACTORS--INDIVIDUAL BEAMS

Air-Void Characteristics of Hardened Concrete

Aggregate	Beam Designation	Durability Factor	Air Content, A (Percent)	Voids per Inch, n	Specific Surface (Sq. in./Cu. in.)	Voids per Unit Vol., N (Voids per cu. in.)	Spacing Factor, L (Inches)
A 1	A21	100	4.5	7.4	660	113,000	0.0075
	A22	99	4.9	9.1	740	173,000	0.0065
	A31	52	3.4	3.8	450	27,000	0.0128
	A32	34	3.2	3.5	440	24,000	0.0134
A 2	B11	90	4.0	7.1	710	127,000	0.0074
	B12	27	3.7	6.4	690	108,000	0.0080
	B21	97	4.8	8.6	720	156,000	0.0068
	B23	53	4.2	7.6	720	141,000	0.0071
	B31	26	3.8	4.3	450	31,000	0.0119
	B32	23	3.2	3.5	440	24,000	0.0134
A 3	C11	96	3.9	6.4	660	97,000	0.0081
	C13	91	4.3	7.2	670	114,000	0.0076
	C31	61	3.5	4.3	490	37,000	0.0114
	C32	87	3.2	4.7	590	57,000	0.0100
A 4	422	62	4.5	7.2	640	104,000	0.0078
	423	85	4.8	8.1	670	130,000	0.0072
	432	60	2.9	3.8	520	37,000	0.0117
	433	100	3.2	5.2	650	78,000	0.0090

Air-Void Characteristics of Hardened Concrete

Aggregate	Designation	Durability Factor	Air Content, A (Percent)	Air Voids per Inch, n	Specific Surface (Sq. in./Cu. in.)	Voids per		Spacing Factor, L (Inches)
						Unit Vol., N (Voids per cu. in.)	Unit Vol., N (Voids per cu. in.)	
A ₄	441	19	3.3	3.4	410	20,000	20,000	0.0139
	442	38	3.7	3.4	370	16,000	16,000	0.0149
A ₅	SA11	80	3.7	5.5	600	69,000	69,000	0.0092
	SA13	99	4.2	7.1	680	115,000	115,000	0.0076
	SA21	94	5.0	9.2	740	176,000	176,000	0.0065
	SA23	95	4.6	9.3	810	214,000	214,000	0.0061
	SA32	90	4.4	7.0	640	100,000	100,000	0.0083
	SA39	92	4.2	7.2	690	120,000	120,000	0.0075
A ₆	SB11	100	10.3	22.2	860	584,000	584,000	0.0043
	SB12	95	9.9	20.5	830	498,000	498,000	0.0044
	SB21	88	5.5	11.5	840	285,000	285,000	0.0055
	SB22	83	5.5	10.7	780	229,000	229,000	0.0059
	SB31	57	3.8	4.9	520	46,000	46,000	0.0107
	SB33	38	3.8	5.1	540	52,000	52,000	0.0100
	SB41	62	4.4	8.6	780	186,000	186,000	0.0065
	SB43	45	4.6	8.3	720	153,000	153,000	0.0069
	SB52	97	6.3	12.7	810	293,000	293,000	0.0053
	SB53	52	6.2	12.8	820	308,000	308,000	0.0052
A ₇	711	100	3.7	6.3	680	103,000	103,000	0.0080
	712	100	3.7	5.6	600	73,000	73,000	0.0090

FORMULAS FOR COMPUTATION OF AIR-VOID
CHARACTERISTICS

The air-void characteristics which were investigated for correlation with durability were:

A = air content, total volume of voids per unit volume of concrete, percent,

n = number of voids intersected per unit length of traverse, voids per inch,

α_c = the specific surface of the air voids, the surface area of the voids per unit volume of air, square inches per cubic inch,

N = number of hypothetical spheres having radius r_h that would equal the actual air content of the concrete, voids per cubic inch, and

L = spacing factor, distance from void boundary to outer boundary of sphere of influence, inches

Two of the characteristics, A and n , were measured directly with the linear traverse integrator. The remaining three were computed from these two measurements with the paste content being introduced in the computation of the spacing factor.

The equations that were used for the computations of α_c , N , and L were presented along with their development in the paper "The Air Requirement of Frost-Resistant Concrete" by T. C. Powers (14) and a discussion of the same paper by T. F. Willis (24).

T. F. Willis (24) showed that regardless of the size distribution of the voids the true specific surface of the voids is given by the equation: $\alpha_c = \frac{4n}{A}$ (Eq. I)

N and L are obtained by assuming that the voids are equal-size

spheres with each sphere having the same specific surface as the measured specific surface. Powers (14) and Willis (24) show that the radius r_h of this hypothetical sphere is equal to $\frac{3}{\alpha c}$ or $\frac{3}{4} \bar{l}$ where:

$\bar{l}$ = the arith mean of the measured chord intercepts.

The hypothetical number of spheres, N , may be computed from the following formula:

$$N = \frac{A}{\frac{\frac{4\pi r_h^3}{3}}{\frac{4\pi (\frac{3}{\alpha c})^3}{3}}} = \frac{A}{\frac{4\pi (\frac{3}{\alpha c})^3}{3}} = \frac{A \alpha c^3}{36 \pi} \quad (\text{Eq. II})$$

Thus the computation of N and L is based on a hypothetical system of uniform-sized spheres having the same volume of air per unit volume of concrete and the same specific surface as the system of random sized voids for which A and n are measured.

To compute the void spacing factor for the hypothetical void system, each sphere is considered to be at the center of a cube with the sum of the volumes of all such cubes and the enclosed spheres equaling the combined air and paste content of the concrete. The "sphere of influence" of each void is the radius of the sphere circumscribing the hypothetical cube. The spheres will overlap except at the corners of the cubes. The radius of the sphere of influence is equal to one-half the diagonal of the cube.

The volume of the single hypothetical cube is $\frac{p + A}{N}$ where p = paste content; sum of volumes of water and cement per unit volume of concrete. Hence, the length of one edge of the hypothetical cube is $\left(\frac{p + A}{N} \right)^{1/3}$.

And,

$$r_m = \frac{\sqrt{3}}{2} \left(\frac{p + A}{N} \right)^{1/3} \quad (\text{Eq. III})$$

where r_m = radius of circumscribed sphere, the "sphere of influence."

The spacing factor L is equal to the difference between the radius of the sphere of influence r_m and the radius of the sphere r_h : that is,

$$L = r_m - r_h. \quad (\text{Eq. IV})$$

Values of A , n , α , N , and L for the 38 beams examined in this study are tabulated in Table 8.

CORRELATION STUDIES

In this study the durability of a given beam was affected by a number of variables in addition to the air-void characteristics. In particular, the coarse aggregate alone could be expected to produce considerable differences in durability among the beams, since six of the coarse aggregates were from sources with poor durability records. For a single concrete mix there is a given number of deleterious particles, and there are an infinite number of combinations in which these particles may be distributed in beams made from the mix. Thus, even within a mix, large variations in durability could exist as a result of differences in the combinations of deleterious particles in the beams. However, since the effect of entrained air on the durability may be different when different aggregates are used, it is believed that by introducing the coarse aggregate as a variable the results of the study have a wider application. Other variables such as efficiency of vacuum saturation, atmospheric temperature, skill of labor, and location of beams within the freezer could have an effect on the durability.

Hence, the beams examined in this study were regarded as a sample randomly selected from a universe of beams in which variables other than the entrained air exist. In order to determine the relative importance of the five air-void characteristics in producing durable concrete, the correlation technique was used to study the relationship between durability and each air-void characteristic. Because of the coarse aggregate and other variables, extremely high correlation coefficients would not be expected.

Linear Correlation--Individual Beams

First, the beams were considered as a sample from a population of beams without regard to their individual constituents or fabrication. The scatter diagram in which the durability factor is plotted against air content is shown in Figure 3. The scatter diagrams using the other air-void characteristics are presented in Figures 4 through 7.

Although it is possible that some curve other than a straight line would give a higher correlation between durability and a given air-void characteristic, it is believed that for the purpose of this study a straight line fitted by the least-squares method is satisfactory. The results of the computations for slopes, correlation coefficients, and regression lines are summarized in Table 9. The t-value for testing the significance of the correlation coefficient is shown. The formula for t was taken from page 88 of Statistical Theory in Research by Anderson and Bancroft (2). The significance of the observed t for n-2 degrees of freedom is indicated in the table as well as the percentage of the variation in durability which is explained by the regression line. The regression lines have been plotted on the scatter diagrams.

Because of the large differences in durability which could be introduced by the coarse aggregate and other variables, these regression lines should not be used to predict the durability factor for a given value of an air-void characteristic. They should be regarded as indicating the trend in the change in durability factor with changes in an air-void characteristic.

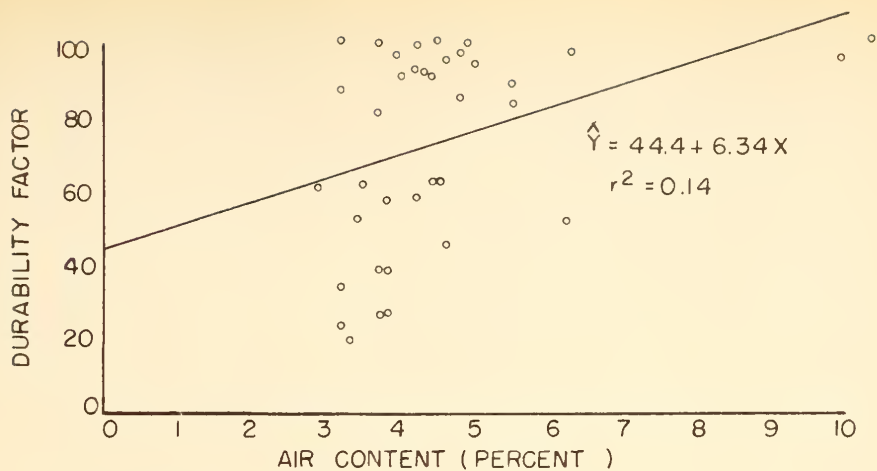


FIG. 3 DURABILITY FACTOR VERSUS AIR CONTENT.

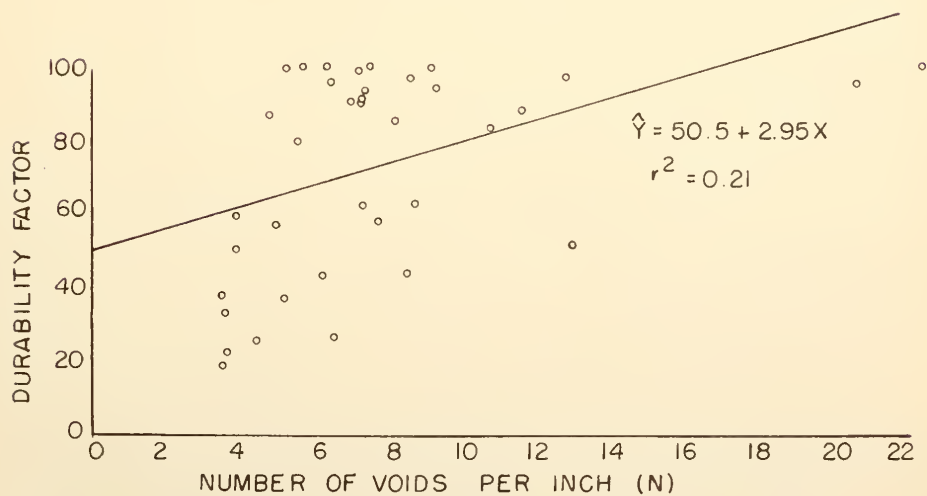


FIG. 4 DURABILITY FACTOR VERSUS NUMBER OF VOIDS PER INCH.

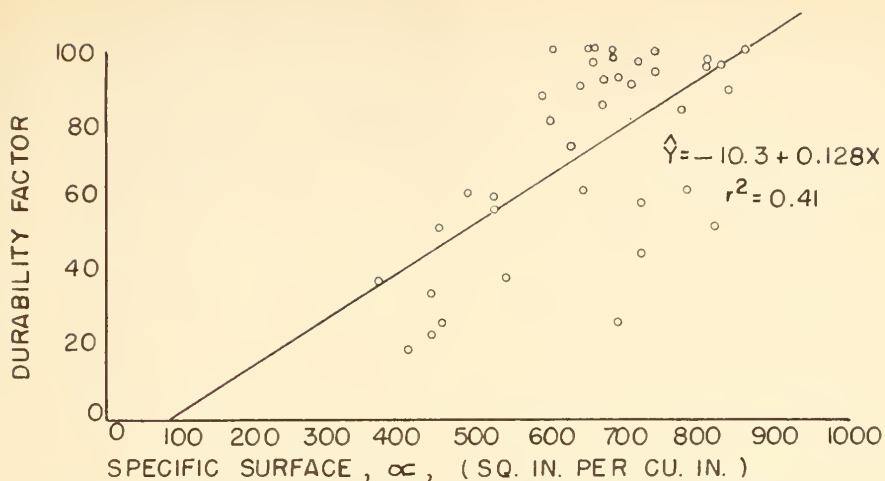


FIG. 5 DURABILITY FACTOR VERSUS SPECIFIC SURFACE

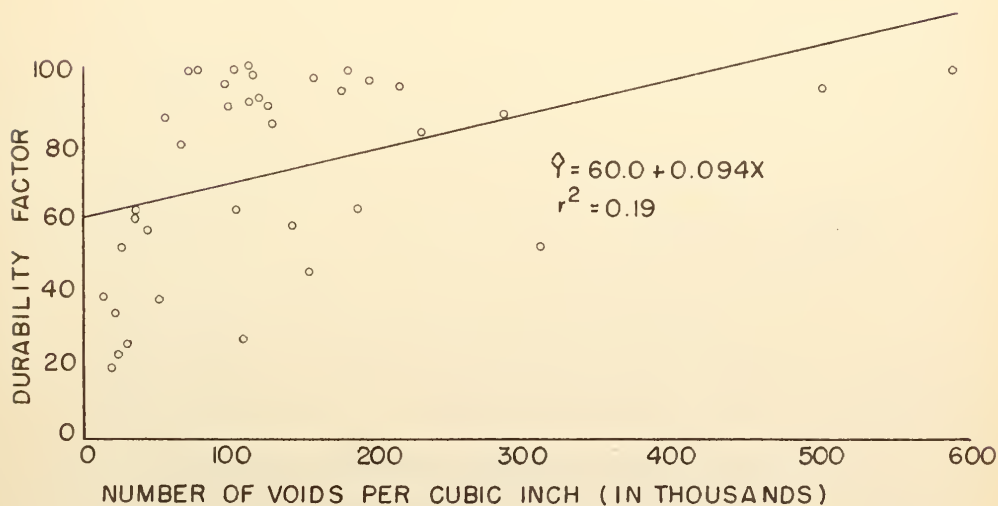


FIG. 6 DURABILITY FACTOR VERSUS NO. OF VOIDS PER CUBIC INCH.

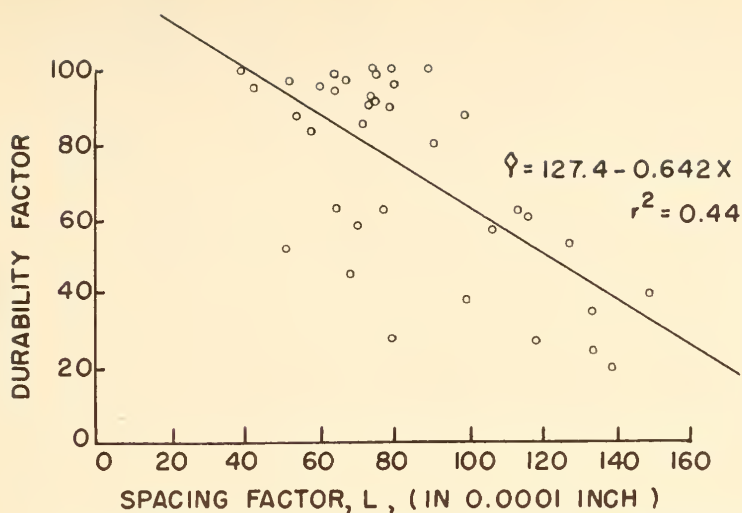


FIG. 7 DURABILITY FACTOR VERSUS SPACING FACTOR.

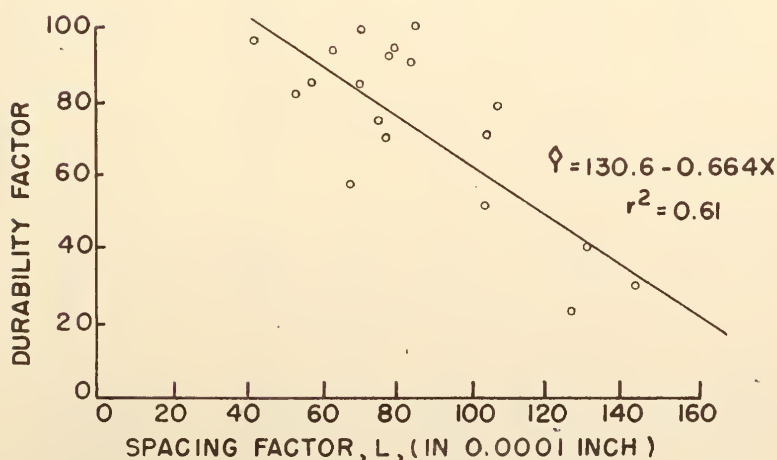


FIG. 8 DURABILITY FACTOR VERSUS SPACING FACTOR -
 AVERAGE VALUES FOR MIXES

TABLE 9

SUMMARY OF STUDY OF LINEAR CORRELATION BETWEEN DURABILITY
AND AIR-VOID CHARACTERISTICS--INDIVIDUAL BEAMS

Air-Void Characteristic	$\bar{Y}$	$\bar{X}$	Slope (b)	Regression Line Y on X	Correlation Coefficient (r)	$t_{\text{obs.}} = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$ Signif- icance	Variation Explained by Regression Line (Percent)
Air Content, A (Percent)	72.9	4.49	6.338	$Y = 44.4 + 6.34X$	0.3698	2.39 *	13.67
Number of Voids per Inch, n	72.9	7.62	2.946	$Y = 50.5 + 2.95X$	0.4542	3.06 ***	20.63
Specific Sur- face, α (Sq.in. per Cu.in.)	72.9	648.2	0.1284	$Y = -10.3 + 0.128X$	0.6370	4.96 ***	40.58
Voids per Unit Volume, N (Thousands of Voids per Cu.in.)	72.9	137.4	0.0941	$Y = 60.0 + 0.094X$	0.4349	2.90 **	18.92
Spacing Fac- tor, L (0.0001 Inch)	72.9	84.9	-0.6416	$Y = 127.4 - 0.642X$	-0.6647	5.34 ***	44.18

NOTE: Y = Durability Factor.

X = Air-Void Characteristic

 $t_{0.9875} = 2.34$ $t_{0.995} = 2.72$ $t_{0.9975} = 2.99$ $t_{\text{obs.}} > 2.34$ $***t_{\text{obs.}} > 2.72$ $***t_{\text{obs.}} > 2.99$

Linear Correlation--Average Values for each Mix

In order to study correlation between durability and air-void characteristics on a mix basis an analysis was made using the average values for each mix. Since freeze-and-thaw data were available on three beams from each mix, the durability factor for each mix was taken as the average of the three beams. Average values for the durability factor and air-void characteristics for each mix are given in Table 10. The value for each air-void characteristic is the average for the two beams from the values given in Table 8. The results of the correlation study are summarized in Table 11.

Discussion of Correlation Studies

The graphs of the durability factor plotted against the five air-void characteristics (Figures 3 through 7) show considerable scatter. Some of this scatter would be expected to result from the coarse-aggregate variable. Inspection of the scatter diagrams alone would lead one to conclude that little correlation exists between the total air content and durability for the beams examined in this study. In the past the total air content has been the air-void characteristic most used in determining the air requirements for frost-resistant concrete.

The air-void characteristics (specific surface and spacing factor) which are computed from equations containing both air content and number of voids per inch show the smallest amount of scatter. This indicates the importance of the interaction of these two characteristics in producing durable concrete. Inspection of Tables 9 and 11, also, shows the importance of the interaction of air content and number of voids per inch in producing durable concrete. The specific surface and void spacing factor give considerably higher correlation coefficients than the other three characteristics.

TABLE 10

AVERAGE AIR-VOID CHARACTERISTICS AND DURABILITY FACTORS
FOR EACH LABORATORY MIX

Air-Void Characteristics of Hardened Concrete

Aggregate	Mix Designation	Durability Factor	Air Content as Measured on Fresh Concrete	Air Content, A (Percent)	Voids per Inch, n	Specific Surface, α (Sq.in./Cu.in.)	Voids per Unit Volume, N (Voids per cu. in.)	Spacing Factor, I (Inches)
A ₁	33-A2	99	4.3	4.7	8.3	700	146,000	0.0070
	33-A3	40	3.8	3.3	3.7	450	26,000	0.0131
A ₂	33-B1	70	3.6	3.9	6.8	700	118,000	0.0077
	33-B2	84	4.7	4.5	8.1	720	149,000	0.0070
	33-B3	23	3.0	3.5	3.9	450	28,000	0.0127
A ₃	33-C1	94	4.4	4.1	6.8	670	105,000	0.0079
	33-C3	78	3.8	3.4	4.5	540	47,000	0.0107
A ₄	34-2	74	4.4	4.7	7.7	660	117,000	0.0075
	34-3	70	3.5	3.1	4.5	590	58,000	0.0104
	34-4	30	3.3	3.5	3.4	390	18,000	0.0144
A ₅	SA-1	90	3.4	4.0	6.3	640	92,000	0.0084
	SA-2	94	4.7	4.8	9.3	780	195,000	0.0063
	SA-3	91	3.7	4.3	7.1	670	110,000	0.0078
A ₆	SB-1	96	9.9	10.1	21.4	850	541,000	0.0042
	SB-2	85	6.2	5.5	11.1	810	257,000	0.0057
	SB-3	51	3.9	3.8	5.0	530	49,000	0.0104
	SB-4	57	4.9	4.5	8.5	750	170,000	0.0067
	SB-5	82	7.5	6.3	12.8	820	302,000	0.0053
A ₇	37-1	100	3.9	3.7	6.0	640	88,000	0.0085

TABLE 11

SUMMARY OF STUDY OF LINEAR CORRELATION BETWEEN DURABILITY AND AIR-VOID CHARACTERISTICS--AVERAGE VALUES FOR EACH MIX

Air-Void Characteristic	$\bar{Y}$	$\bar{X}$	Slope (b)	Regression Line Y on X	Correlation Coefficient (r)	$t_{\text{obs.}} \sqrt{\frac{n-2}{n-1}}$	Signif- cance	Variation Explained by Regression Line (Percent)
Air Content, A (Percent)	74.1	4.51	6.202	$Y = 46.1 + 6.20X$	0.4134	1.87	#	17.09
Number of Voids Per Inch, n	74.1	7.64	2.903	$Y = 51.9 + 2.90X$	0.5138	2.47	***	26.40
Specific Surface, α (sq. In. per Cu. In.)	74.1	650.5	0.1338	$Y = 12.9 + 0.134X$	0.7460	4.62	****	55.66
Voids per Unit Volume, N (Thousands of Voids per Cu. In.)	74.1	137.7	0.0940	$Y = 61.2 + 0.094X$	0.4952	2.35	**	24.53
Spacing Factor, L (0.001 Inch)	74.1	85.1	0.6641	$Y = 130.6 - 0.664X$	0.7792	5.13	****	60.72

NOTE: Y = Durability Factor.

X = Air-Void Characteristic

$$t_{0.95} = 1.74 \quad t_{0.975} = 2.11$$

$$t_{0.9875} = 2.46$$

$$t_{0.9975} = 3.22$$

$$t_{\text{obs.}} > 1.74$$

$$t_{\text{obs.}} > 2.11$$

$$t_{\text{obs.}} > 2.46$$

$$t_{\text{obs.}} > 2.90$$

$$t_{\text{obs.}} > 3.22$$

Tables 9 and 11 show that the correlation coefficient obtained using the average values for each mix is noticeable higher for each air-void characteristic than the corresponding value computed from the data for individual beams. This results from eliminating the large differences in durability between beams within the same mix by means of averaging the individual values. A large amount of this difference in durability within a mix can be attributed to the coarse aggregate, in that differences in the combinations of deleterious particles in the beams results in variations in durability.

Table 9 shows that 44 percent of the variation in durability can be attributed to differences in void spacing based on the data for individual beams while Table 11 shows a corresponding value of 61 percent using average values for each mix. In Figure 8 durability factor is plotted against void spacing using the average mix values. Comparison with Figure 7 shows considerable reduction in scatter when mix values are used.

Although there may be a better way to express the size and distribution of the air voids in portland cement paste than the spacing factor used in this study, the results of the correlation studies emphasize the importance of size and distribution in producing frost-resistant concrete.

SUMMARY OF RESULTS

The results of the work completed in this investigation may be summarized in the following manner,

1. The measurement by the linear traverse technique of air content and number of voids per inch of a particular beam may be considered as one long traverse without regard to the position or length of the individual traverses. The standard error of the mean is approximately the same (0.3 for the beams examined in this study) whether four-, six-, eight-, or ten-inch traverses are used as long as the total length of the traverses is the same.
2. For the beams examined in this study, the selection of 200 inches of traverses gave values for the air content within ± 0.5 percent of the true value and the number of voids per inch within ± 0.5 void per inch of the true value at the 90 percent confidence level.
3. The accepted theoretical explanation of the action of entrained air in producing frost-resistant concrete demonstrates the importance of the size and distribution of the air voids. The correlation studies of the relationship between each of the air-void characteristics and durability show the void spacing factor to be most highly correlated with durability factor. Using the data on individual beams, 44 percent of the differences in durability could be explained by the differences in the void spacing factor. Using average values for each mix, 61 percent of the differences in durability could be explained by differences in the void spacing factor. Thus, this investigation essentially substantiates the theory.
4. The specific surface was almost as highly correlated with durability as the void spacing factor with 41 percent of the variation in

durability being explained by the differences in the specific surface when the data on the individual beams were used. Using average values for each mix 56 percent of the variation in durability could be explained by differences in the specific surface.

5 The five air-void characteristics ranked in the order of their correlation with durability beginning with the one showing the best correlation are: (a) spacing factor, (b) specific surface, (c) number of voids per inch, (d) hypothetical number of voids per cubic inch, and (e) total air content.

6 Since the specific surface was almost as highly correlated with durability factor as the void spacing factor, either of these two characteristics is probably a satisfactory guide for determining the air requirements for frost-resistant concrete. The correlation between each of these two characteristics and durability was found to be highly significant at the 99.75 percent confidence level.

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